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iFly

Safety, Complexity and Responsibility based design and
validation of highly automated Air Traffic Management

Specific Targeted Research Projects (STREP)

Thematic Priority 1.3.1.4.g Aeronautics and Space

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Comparative Study of Conflict Resolution Methods
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Comparative Study of Conflict Resolution Methods

Abstract

This is the first deliverable of the work package WP5 of the project iFly. The purpose of this report is to present a survey of different methods proposed for conflict. Both centralized and decentralized conflict resolution methods are considered. Emphasis is placed on methods that provide proven performance and arise both in the autonomous aircraft/free flight communities and in potentially related fields such as robotics and mathematical finance. The methods are analyzed and compared in terms of their capabilities, limitations and complementarities from a general autonomous aircraft conflict resolution perspective.

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1 Introduction

The main scope of Deliverable D5.1 is to review, describe and compare Conflict Resolution methods found in literature and used in practice. For this purpose, a survey of different methods for conflict resolution in the literature has been carried out. As described in the Description of Work of iFly, both centralized and decentralized methods have been considered. The main emphasis is placed on methods that provide proven performance and arise both in the autonomous aircraft/free flight communities and in potentially related fields (such as robotics and mathematical finance). The methods reviewed are classified in three different categories:

- Long term conflict resolution algorithms

- Mid term conflict resolution algorithms

- Short term conflict resolution algorithms

The most important methods in each of these categories have been reviewed and analyzed in terms of their capabilities, limitations and complementarities from a general autonomous aircraft conflict resolution perspective.

The deliverable is organized as follows. Section 2 provides an overview of the different classification criteria for CD&R methods. Section 3 reviews the main algorithms in the long term conflict resolution (with resolution horizons larger than an hour), Section 4 focuses on algorithms operating in the mid term (horizons of tens of minutes), while Section 5 describes algorithms for short term conflict resolution (horizons of minutes). Section 6 discusses the main differences between centralized and decentralized approaches in conflict resolution algorithms. Section 7 describes the important technological aspects related to the three levels of conflict resolution and discusses the necessary technologies needed for the conflict resolution algorithms. Finally, Section 8 summarizes the main conclusions and findings of D5.1.

2   CD&R Classification

Conflict Detection & Resolution (CD&R) methods can be analyzed based
on the following factors:

1. Centralized versus decentralized (see Section 6)

2. Required information,

3. Conflict Detection approach,

4. CR Objectives (optimization, performance, etc).

As shown in Figure 1, the relative importance of these factors for CD&R
applications vary with considered look-ahead time.
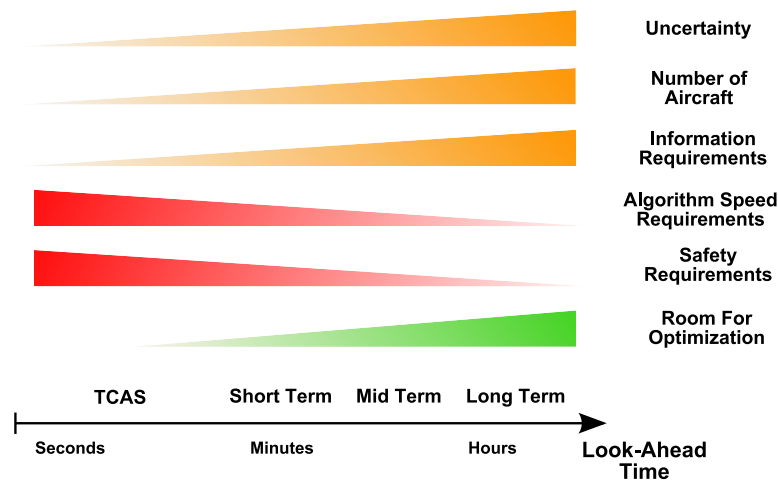
Figure 1: Evolution of CD&R objectives with look-ahead time.

2.1   Airborne vs. Ground CD&R (a.k.a. centralized versus decentralized)

As many of the existing CD&R methods were developed for ATC ground-
based centralized system, it is useful to start with a short discussion about
important differences between airborne (distributed) and centralized ap-
proaches to Conflict Resolution.

- The ground system has the authority to decide which aircraft will
  maneuver and how, while an airborne system can independently ma-
  neuver its own aircraft. Even if there is a cooperative CR method
  or priority rules, for safety reasons an ASAS application must always
  be able to solve situations without the cooperation of the conflicting
  aircraft.

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- Airborne systems will try to perform the flight in the optimal way, as defined by its stakeholder(s). Ground based systems will try to optimize the global situation.

- Airborne systems have access to the most up-to-date information about the local situation (aircraft state and environmental conditions) and thus should be used for dynamic control during the flight.

- Ground systems must typically handle a higher number of aircraft while an airborne system must solve a smaller local subset of the global traffic situation.

- Ground systems have access to global information (e.g. weather forecasts). Therefore, they are in a better position to carry out global optimization tasks.

- Airborne systems have limited computational power as compared to ground systems.

2.2 Required Information

The usual classification of CR methods, which is also used within this report, is based on the required traffic information.

Long Term CD&R is usually referred to as flow or trajectory management. As these applications handle large areas, i.e., high number of aircraft, they are based only on the macroscopic description of the flights (flight plan) and environment (airport/ATC capacities, hazard weather areas, etc). So the temporal horizon for a ground-based flow management is between hours and months. In case of a partial delegation of this functionality (e.g. weather/congestion avoidance) to onboard applications, this threshold may shift to a shorter time horizons (probably tens of minutes).

Mid Term CD&R is based on updated information about aircraft intended trajectory (usually referred to as "intent"). This information typically represents some kind of description of the 4D trajectory over a time horizon of 15-20 minutes. The most effective intent description is still intensively being studied (new versions of ARINC 702a standard).

Short Term CD&R is usually based on just the state information that is extrapolated into the future. As the reliability of such description decreases quickly with look-ahead time, this kind of algorithm generates a lot of false alarms for longer time horizons. In this context, the maximum useful time range (in the current airways-based environment) is about 5-6 minutes.

2.3   Conflict Detection

Any information about future trajectory inevitably contains some amount of uncertainty that may or may not be considered by a CD algorithm. The **probabilistic approach** considers probabilistic distribution of possible future trajectories. An important advantage of this method is the flexibility to adjust an alert threshold (probability of a conflict that generates an alert) to find a balance between the safety and false alarm rate. However, it usually demands higher computational power.

The probabilistic approach covers, as special cases, two other frequently used methods:

The deterministic approach (one trajectory with the probability of 1.0) is computationally the simplest, tends to reduce false alarms rate, but the reliability may also be considerably reduced.

The worst-case approach that makes all feasible trajectories equally probable. In this way safety is maximized, but on the other hand, the rate of false alarm is very high.

2.4   CR Objectives

Conflict Resolution objectives include:

1. CR maneuver type,

2. CR coordination method,

3. Complexity,

4. Constraint handling,

5. Optimization

2.4.1   CR Maneuver Type

A typical flight is executed as a sequence of well known flight procedures (guidance modes in the FMS terminology). Consequently a set of the considered resolution maneuvers can be naturally chosen to be a subset of these procedures. A maneuver can be defined by a geometrical pattern or by specifying a new guidance or trajectory target (the autopilot or FMS approach discussed below).

The choice of possible CR maneuvers can also be dependent on the look-ahead time of the Conflict Detection module. For example, an effective speed-based conflict solution typically requires at least medium-term time horizon (about 15-20 minutes). This is not only a consequence of a limited size of the aircraft speed envelope but also due to considerably higher flight costs induced by larger speed changes.

Typical maneuver types used in the current methods are the following:

- Horizontal maneuvers (turns),

- Vertical maneuvers,

- Speed changes,

- Full 3D maneuvers.

2.4.2 CR Coordination Method

There are basically two different approaches to distributed CR:

- **Cooperative CR** where conflicting aircraft coordinate their CR maneuvers.

- **Non-cooperative CR** where each aircraft solves the situation without a coordination with the conflicting aircraft.

Cooperative methods typically result in more effective maneuvers, however, there is an additional safety risk related to the lack of communication. They may also increase the pilot's workload.

Non-cooperative methods usually result in excessive maneuvering and there is even a possibility that conflicting aircraft generate conflicting maneuvers. The latter problem may be solved by so-called *implicit coordination* based on the use of compatible (e.g. geometrical) algorithms or simple flight rules. Excessive maneuvering may then be reduced by use of some kind of priority rules.

Note that the centralized CR is always assumed to be coordinated in the above sense.

2.4.3 Complexity

Complexity, extensively studied in iFly's WP3, is another aspect that may be considered within CR maneuvers. From the point of view of CR one can identify two approaches to solve conflicting situations:

- Pairwise (i.e., a sequential resolution),

- Solving multiple aircraft situation at once. This approach is usually preceded by so-called clustering where the group of aircraft involved in the conflict is determined.

2.4.4   Constraint handling

Even within an autonomous flight, aircraft are typically subject to several constraints (flow management, restricted areas, speed envelope, hazard weather, etc.). The simplest one is represented by the entry condition to the ATC-managed airspace (e.g. TMA). Thus for a potential ASAS application it is essential to be able to consider these constraints when a CR maneuver is generated.

2.4.5   Optimization

One of the crucial benefits of the autonomous aircraft concept is the flexibility of dynamic optimization during an autonomous part of flight. Obviously this optimization may be computationally and time demanding and thus it becomes important that potential conflicts are detected early, optimally within the mid-term time horizon of tens of minutes. Even when optimization procedures are too computationally demanding, some kind of heuristic approaches may be used instead.

3   Long Term Conflict Resolution

Long Term Conflict Resolution in ATM is referring to the construction of the flight plans, such that the probability of conflict within the next hours is minimized. This task is quite critical, since a bad scheduling of flight plans can result in more need for actions in the mid term and short term conflict resolution phases. More often, the term Air Traffic Flow Management (TFM) is used to describe conflict resolution in horizons of hours/days.

Since the levels of uncertainty are quite high for these horizons, it is not really possible to perform a conflict resolution. Instead the aim is to deal with congestion problems. Congestion occurs whenever the capacity of airport runway systems and/or ATC is exceeded over a period of time. Thus, it is mostly associated with the peak travel hours of the day, as well as with periods of poor weather conditions when airport and en route sector service rates can be significantly reduced. Traffic congestion is a critical problem in all developed air transportation systems and it results to big costs for airline companies, as well as time delays for the passengers.

TFM attempts on a day-to-day basis to "match", dynamically, the air traffic demand with the capacity of the airports and airspace sectors of the ATC system. Usually, TFM problems are solved via *ground-holding* techniques, where aircraft are delayed before they take off. Besides determining release times for aircraft though, the TFM problem also determines the optimal speed adjustment of aircraft while airborne for a network of airports taking into account the capacity of the airspace. Thus, the TFM problem determines how to control a flight throughout its duration, not simply before its departure. If we add the final complication, rerouting of flights due to drastic fluctuations in the available capacity of airspace regions, we obtain the Air Traffic Flow Management Rerouting (TFMR) problem. In this problem, a flight may be rerouted through a different flight path in order to reach its destination if the current route passes through a region that is unusable for reasons usually related to poor weather conditions.

Work done in the field of TFM can be better understood, if we consider the following modeling classification:

- Deterministic vs. stochastic models, which are distinguished by whether the capacities of the system (airports and sectors in the airspace) are assumed deterministic or probabilistic; see also Section 2.3.

- Static vs. dynamic models, which are distinguished by whether or not the solutions are updated dynamically in time.

Several ways of dealing with TFM problems have been suggested in the literature. In [5], Bertsimas and Odoni present a survey of optimization models for the problem of TFM. The taxonomy of the different methods they propose will be followed later on in this part of the deliverable.

3.1 Ground-holding

Ground-holding is typically imposed on aircraft flying to congested airports or scheduled to traverse congested airspace. It can be defined as the action of delaying take-off beyond a flight's scheduled departure time. The main idea behind this strategy is that as long as a delay cannot be avoided, it is safer and more cost-efficient for the flight to absorb the delay before take-off, while on ground. The use of ground-holding techniques is relatively new, as it was only in the beginning of 1980s that they started being widely used. More specifically, during the 1981 air traffic controllers' strike in the United States, it was introduced as a way to reduce controller workload by limiting the number of aircraft that were airborne at any given time.

The models suggested for the Ground-Holding Problem (GHP) are of a tactical nature, attempting to assign ground holding delays to flights, with the objective of minimizing the cost of delays to airline operators, while existing constraints on ATM capacities are satisfied. The GHP can be divided into two subproblems, as they are found in literature, the *Single-Airport Ground Holding Problem* (SAGHP) and the *Multi-Airport Ground Holding Problem* (MAGHP). In the SAGHP, only flights scheduled to travel a specific (that the available capacity is may be exceeded within the day of interest) are assigned ground holding times. In the MAGHP, an entire set of airports is simultaneously examined, where delays are assumed to propagate, as aircraft perform consecutive flights. The GHP can be further divided into deterministic GHPs and stochastic GHPs. The stochastic GHPs take also into account the uncertainty present, that makes the decision for the ground-holding delay difficult, since sector and airport capacities are often highly variable, as they are very sensitive to weather changes or other events. Under such circumstances, ground-holding decisions must be robust under uncertainties, trying at the same time not to produce over-conservative strategies.

3.1.1 Single-Airport, Ground-Holding Problem (SAGHP)

For many practical situations, the most general version of the SAGHP (dynamic and stochastic) need not necessary be appropriate. Alternative versions of the SAGHP may have to be solved, depending on the information available and how this information is updated. Several different versions of this problem have been addressed in literature. For example, in locations where the weather and/or the airport capacities can be approximated as perfectly predictable quantities, deterministic versions are preferable. Similarly, in environments where either information concerning weather or capacities at a set of geographically dispersed locations is not updated frequently or an initial ground-holding plan is prepared at a single point in time (typically at the beginning of the day) and that plan is revised only in a marginal way from that point on, static versions may be more appropriate. Hoffman and

Ball in [44] present a very good description of the deterministic SAGHP and the ways it is addressed through the literature.

3.1.2   Multi-Airport, Ground-Holding Problem (MAGHP)

MAGHP models consider many airports simultaneously. Despite this fact though, the best available models in this area are not extensions or derivatives of SAGHP models. In the case that many airports are considered, mutual dependence is caused by those aircraft that perform several sequential flights. For example, a flight departure has to be delayed whenever the preceding flight, performed by the same aircraft, has suffered an excessive delay. This fact increases the difficulties of solving these problems.

Extension to the Multi-Airport case was first suggested by Vranas, Bertsimas and Odoni in [86] for the static deterministic case and in [85] for the stochastic dynamic case. In [6], Bertsimas and Patterson introduced a new model, slightly different from the one proposed by [86] in that it allows for more efficient linear programming relaxations of the mixed integer linear programs that need to be solved. The performance of the mentioned models (only for the deterministic cases) was evaluated by Andreatta and Brunetta in [1] on a set of seven test instances: they demonstrated that the model in [6] is the one that works best.

The model principle for the MAGHP is the following [1]: *MINIMIZE* the total costs due to delays subject to the following families of constraints:

- capacity constraints (the number of landings should not exceed the capacity at any given airport during any given time period)

- assignment constraints (for any given flight a period of time for landing must be selected within an appropriate time window)

- coupling constraints (takeoff time for a flight must be scheduled after the landing time of a preceding connecting flight, plus some extra turnaround time)

- integrality constraints (meaning that an aircraft cannot land a piece at a time)

All the above models are Integer Linear Programming models. Their main differences lie in the choice of the integer variables being used in the optimization problem. Although all the methods make it possible to solve optimally instances of realistic size, the computation time they require is far too long for application purposes. As a result, it is necessary to resort to heuristics, in order to get a suboptimal solution quickly. In [2] a good heuristic is proposed, successfully tested on the seven sample instances of [1]. In [3] a new improved heuristic is presented, tested on a wider test bed of 32 instances of large size (up to 5000 flights and 10 airports). Another

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heuristic method is presented in [67], using a similar formulation. All these methods refer to the static deterministic model.

Significantly less work has been done in the stochastic and dynamic case. Although, already introduced by [85], there seems to be no major work under this field. This is surely a field where a lot of work can still be done.

3.2   Generalized TFM problem

This is the most general version of the TFM, where in addition to determining release times for aircraft (ground-holds), we also have the possibility of assigning some airborne delays to flights at specific points on their route. These delays could be absorbed through different ways, e.g. airborne holding at these points or exercising speed control.

One could define additional problems and types of models in this category. For example, take the Traffic Flow Management Rerouting Problem (TFMRP). Here, a flight may be re-routed in real time, if the current route passes through a region that unexpectedly becomes congested or should be avoided for other reasons, usually related to poor weather conditions.

Five distinct types of existing models in literature for the GTFMP can be identified, as described in [5]. They fall into two categories:

- Models attempting to find an optimal solution for the problem. The approaches of Bertsimas and Stock Patterson in [6], the Time Assignment Model [11, 12, 61] and the Space-Time Network [41] fall into this category.

- Models aiming at an approximate solution. The Multiple Airport Scheduler [27], as well as the operational CASA [73] fall in this category.

There are many common characteristics between these model types. First, the ATM infrastructure (airports, terminal areas, navigation fixes, en route sectors, airways) is viewed as a multiple origin-destination network on which traffic flows (that may vary over time) have to be assigned. Second, it is always assumed that available capacity as well as flight demand is known in advance. Third, in four of the five cases, the models deal with uncertainty by essentially assuming that the GTFMP will be solved anew every time conditions change, i.e., whenever capacity and/or demand change sufficiently to warrant such re-solving of the GTFMP (e.g. every few hours). However, the Computer Assisted Slot Allocation (CASA) heuristic recognizes uncertainty more explicitly by setting aside a number of flight slots for last minute contingencies.

The first optimal approach is the one by Bertsimas and Stock Patterson [6], where, the problem is formulated as a 0-1 Integer Programming problem with six sets of constraints, with the objective to minimize the total cost

of delaying aircraft on the ground and in the air. The first three sets of constraints ensure that the traffic flows will not exceed the departure capacity of any airport in the network, the arrival capacity of any airport and the sector capacity of any sector, respectively. The other three sets of constraints represent the connectivity constraints in the problem: connectivity between sectors, between airports and in time. Respecting those constraints ensures that the traffic flows recommended by the model will be meaningful physically. On the other hand, the resulting optimization model is quite complex.

The second major existing GTFMP model is the Time Assignment Model or TAM [11, 12, 61]. This has a similar 0-1 Integer Programming formulation, with an optimization model comprising five sets of constraints and the same cost function as the previous one. The first set of constraints specifies that capacities cannot be exceeded; the second defines a lower bound for the flight time from one node ("fix") of the underlying network to the next; the third specifies that each flight can pass over any particular fix only once; the fourth gives the earliest time interval during which a flight may depart; and the last set of constraints specifies a minimum "turn-around" time on the ground for each aircraft between flight legs. Some of those restrictions are also defined implicitly in the [6] model, through the connectivity constraints.

The third optimization model is the Space-Time Network (STN) [41]. This model is formulated as a multi-commodity minimum-cost flow on a network. Instead of individual flights, it deals with aggregate flows, attempting to minimize the total delay costs (including departure, en route and arrival capacity constraints). Unfortunately, its computational performance has been quite disappointing and efforts toward its further development have been abandoned.

The first heuristic approach, the Multiple Airport Scheduler (MAS) is a hybrid of optimization routines and heuristics [27]. Information about this model, which was developed in connection with the Advanced Traffic Management System of the FAA, is limited, because little has been published about it.

The second heuristic, CASA, is described in [73] (see also [29]). This heuristic gives priority to flights on a "First Planned, First Served" (FPFS) basis, i.e. the flights with the earliest departure times are considered first. CASA thus considers departing flights sequentially and, when necessary, assigns to each a ground-holding delay consistent with the most restrictive capacity constraint that the flight will encounter between its origin and its destination. A portion of the available capacity is reserved for short-haul flights and flights that may file a flight plan shortly before their intended departure time, in order to avoid cases where all available slots are consumed by long-haul flights, that file flight plans early and have early departure times. CASA also automatically updates its solutions every few minutes, hoping that, as conditions change, the algorithm may discover better slot

allocations. CASA is very efficient computationally, typically returning solutions within about half a minute for problems that would be considered large for an optimization model. On the other hand, there is no theoretical guarantee, neither anything else suggesting that these solutions are close to optimal.

Recently, in [68] and [20] the traffic flow management problem with stochastic weather is addressed. [20] tries to reduce the amount of wasted capacity caused by weather events (e.g. entirely avoiding storm zones that have a good chance of vanishing in the near future) by solving the optimal path planning problem in a framework that models both the weather patterns and the sector capacity constraints. The algorithm complexity grows linearly with the number of aircraft, provided that a priority order is given ranking the various aircraft priorities. Along the same lines is also the work in [68], where multi-aircraft situations are addressed, using a stochastic dynamic programming algorithm that provides a dynamic routing strategy that minimizes the expected delay of the overall system, while taking into consideration the constraints obtained by the sector capacities. Unfortunately, computational costs can become high when this algorithm is introduced even with a relatively small number of aircraft.

Wanke and Greenbaum in [87] suggest an online decision making process for congestion avoidance. Their approach is probabilistic and focuses on minimizing the congestion probability under some presence of uncertainty due to weather forecast errors that leads to inaccuracies in sector capacity prediction. The proposed resolution horizon for this problem is less than 90 minutes, while the problem is solved in a centralized fashion. It is important to note though that the incremental approach followed can potentially allow to apply part of the solution in a decentralized manner.

3.3   Central Flow Management Unit - CFMU

The CFMU [29] is an operational unit of EUROCONTROL, enhancing safety through coordinated management of the air traffic in Europe. It ensures congestion in the air does not occur and that available capacity is used effectively.

CFMU addresses the TFM problem in a generalized way, using the *Air Traffic Flow and Capacity Management* (ATCFM) service. As described in [28], ATFCM is a service that is enhancing TFM with the objective of managing the balance of demand and capacity by optimizing the use of available resources and coordinating adequate responses, in order to enhance the quality of service and the performance of the ATM system. It comprises 3 different phases:

1. *Strategic Flow Management* takes place seven days or more prior to the day of operation and includes research, planning and coordination

activities. This phase consists of analyzing the evolution of the forecast demand and the identification of potential new problems and in evaluating possible solutions. The outputs of this phase are the capacity plan for the following year, the Route Allocation Plans and sets of other plans that can be activated as necessary during the next phases.

2. *Pre-Tactical Flow Management* is applied during six days prior to the day of operation and consists of planning and coordination activities. This phase analyzes and decides on the best way to manage the available capacity resources and on the need for the implementation of flow measures (regulations or routings). The output is the ATFCM Daily Plan (ADP) published via ATFCM Notification Message (ANM) and Network News.

3. *Tactical Flow Management* is applied on the day of the operation. This phase updates the daily plan according to the actual traffic and capacity. The management of the traffic is made through slot allocation and/or ad-hoc reroutings.

It has to be noted that all ATFCM processes, emphasize on enabling Airline Operators (AOs) to choose between the concepts of acceptable delays on one hand and preferred routings on the other. The main ATFCM processes are:

• Network Operations Plan, which is a document providing a consolidated view of the forecast seasonal ATFCM situation. This is published twice a year and updated usually twice per season.

• Route Planning Processes, which comprises all the information published by CFMU concerning route restrictions, rerouting possibilities and the processes involved in deciding to reroute a flight vary according to the phase of activity. It can be further divided into strategic route planning, routing scenarios (that are reroutes to help resolve forecast ATC capacity problems) and tactical rerouting (that identifies flights subject to delays that would benefit from a reroute).

• Slot Allocation Process, that allocates slots for flights, using the CASA system.

• Slot Adherence, assuring the compliance to the slots assigned for flights.

• Position Reporting for flying aircraft.

• Management of Unusual Situations, such as low visibility, strikes etc.

As already mentioned before, CFMU handles TFM in a heuristic way. The latest version of CFMU system is 12.0, while operational is the 11.0.

3.4   Concluding Remarks

This chapter has presented a review of a number of approaches to solving Traffic Flow Management problems. Table 1 provides a brief classification of methods according to the categories described in this chapter.

Approach	SAGHP/ MAGHP/ GTFM	Deterministic/ Stochastic/ Both	Static/ Dynamic/ Both	Optimal/ Heuristic/ Both
[44]	SAGHP	B	B	B
[86]	MAGHP	D	S	O
[85]	MAGHP	S	D	O
[6]	GTFM	D	S	O
[2]	MAGHP	D	S	H
[3]	MAGHP	D	S	H
[67]	MAGHP	D	S	H
[11, 12, 61]	GTFM	D	S	O
[41]	GTFM	D	S	O
[27]	GTFM	?	?	H
[73]	GTFM	D	D	H
[20, 68]	GTFM	S	D	O

Table 1: Summary of Characteristics of Long-Term Conflict Resolution Algorithms.

As it has become clear from the algorithms presented, the traffic flow management problem is difficult to solve in a decentralized way by the flying aircraft, since it involves more strategic decisions for the system over horizons far larger than the average aircraft flight time. For all the existing Long Term CD&R algorithms, global knowledge is of great importance, while aircraft exact positions and velocities are not important, since the planning takes place prior to a flight. Moreover, TFM algorithms are the most computationally intensive algorithms and (usually) aim at a globally optimal (or close to optimal) solution for the system, making decentralization difficult for this problem. Long-Term CD&R can be implemented in the context of A^3 concept integrated in the SESAR concept, possibly determining a RBT for the flights. In the Autonomous Aircraft Advanced (A^3) concept, where aircraft use a decentralized control strategy and rely only on local information in order to avoid and resolve conflicts, only some part of the Long-Term CD&R can be carried out in a distributed fashion (e.g. weather avoidance).

4   Mid Term Conflict Resolution

In current ATM each aircraft is considered to lie inside its *Protected Airspace Zone* which is of cylindrical shape, defined by a minimum horizontal separation (i.e. the radius of the cylinder) and a minimum vertical separation (the cylinder's height). Minimum horizontal separation is usually set to 5nm, while vertical separation can be no less than 2000ft for an altitude of 1000ft to 40000ft, unless RVSM (Reduced Vertical Separation Minima) is applied and the minimum vertical separation is 1000ft. If the protected zone of an aircraft is violated by another aircraft, i.e. when their distance becomes less than the radius of their protected zones, then the two aircraft are in conflict.

In current air traffic control, the goal of conflict detection and resolution is to make a prediction whether a conflict is likely to occur in the future, communicate the detected conflict to an operator and assist in the resolution of the conflict. Given some intent information and a trajectory prediction model a conflict detection procedure is executed with a view to detecting impending conflicts. The Air Traffic Controller (ATC) may then be informed by a suitable alerting mechanism.

This section contains an assessment of (current and potential future) approaches for near to mid-term conflict detection and resolution. The horizon lengths under consideration are in the order of tens of minutes. A comparative survey of the key methods identified in the literature is performed. Emphasis is placed on automated (self separation) techniques. The evaluation criteria include: dimensions of state information (horizontal plane or three-dimensional); prediction models; technology readiness level (TRL).

4.1   Prediction Models

The classification methods of the prediction models fall into the following categories; deterministic, stochastic and worst case modelling. The ability to compute a reliable prediction of the trajectory of an aircraft on a future horizon of the order of tens of minutes is an essential part of Air Traffic Control. Increasing levels of traffic both in Europe and in the US demand more advanced trajectory prediction algorithms in order to sustain the performance of ATC.

A trajectory prediction is calculated on the basis of the aircraft estimated position and state, some intent information, weather information and a performance model, (e.g. the aircraft performance model developed by the EUROCONTROL Experimental Centre in BADA [36]). The aircraft position and state can be estimated from radar measurements or can be broadcast by the aircraft itself, such as in the Mode-S [15] and ADS-B [78] systems. The intent information includes controller instructions and operational procedures (e.g. how a descent is executed). The weather information includes predicted winds and temperature profiles. The performance

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model describes the aircraft dynamic behavior. Commercial aircraft in level flight can be well modeled by simple kinematic models - see e.g. [70]. More complex performance models are needed only to calculate trajectories which include a vertical displacement, see e.g. [36]. In a prediction over a future horizon of the order of tens of minutes there is unavoidable uncertainty. In the seminal papers [71], [72] on the use of trajectory prediction to assess the probability of a future loss of safe separation between two aircraft (conflict probability), the approach for taking into account uncertainty is to super-impose a distribution of position errors on a predicted nominal trajectory. The shape of the distribution of position errors is estimated on the basis of previous radar track records - see also [88]. In [48] simple kinematic models driven by a stochastic wind field are used to investigate the effect of spatial wind correlation on conflict probability in level flight. Chaloulos and Lygeros[13] present a similar study based on Monte Carlo simulations of a more sophisticated wind model.

In contrast to the probabilistic detection methods described, worst case assumptions have been adopted for example in [81], for the purpose of designing safe manoeuvres to resolve the encounter of a set of aircraft in level flight.

Conflict detection in [57] is performed in both two-dimensional and three dimensional cases, in both deterministic and nondeterministic settings. They consider also various types of warning procedures, including tactical warnings issued prior to entry into the protected airspace zone, methods based on overlap of reachability sets of the aircraft in the potential conflict and conflict probability maps to establish alert zones around the aircraft.

4.2   Conflict Resolution

In addition to the categories of deterministic, stochastic and worst case modelling discussed earlier, conflict resolution methods are further classified according to:

1. Number of Aircraft

   (a) Pairwise Conflicts
   (b) Multiaircraft conflict

2. Manoeuvre Type

   (a) Turns
   (b) Speed changes
   (c) Altitude changes
   (d) Combination of the above

A large body of work focusing on pairwise conflicts exists, for instance [16] and an excellent review can be found in [59]. It is useful however to consider the global aircraft conflict problem. Treatment of the multiple aircraft case is more rare. Conflicts involving more than two aircraft have been shown to occur in high density sectors. Furthermore, whilst conflicts involving more than two aircraft are infrequent, indirect conflicts can occur as a result of the solution of a pairwise conflict giving rise to a secondary conflict with a third, neighbouring aircraft, the so-called domino effect. Typically manoeuvres for resolving conflicts comprise the following actions; turns, altitude change and acceleration. Strategies involve performing any single one or combination of these actions. The majority of models consider state information purely in the horizontal plane, though some additionally consider the vertical dimension.

Methods for solving conflict resolution fall into the categories of rule-based and optimised approaches. The latter are more favourable when handling situations arising with multiple conflicts, where explicit elicitation of complex rules is not feasible. Generally, conflict resolution manoeuvres are chosen by minimising a certain cost function with safe separation constraints. Contributions belonging to this class include [38], [47]. In the former, the planar multiple conflict resolution problem is formulated as a nonconvex, quadratically constrained quadratic program. This is approximated by a convex, semidefinite program, combined with a branch and bound search. Optimisation is performed over all crossing patterns, bypassing the need for knowledge of the crossing pattern among aircraft in advance. Another example of objective optimisation for solving the conflict resolution is the approach proposed in [74, 75]. Here the aircraft models are more complex with detailed nonlinear point mass dynamics. They use continuous variables to formulate the cylindrical safety zone, and convert the optimal control problem into a finite dimensional nonlinear program. Interior point algorithms following a barrier approach are employed to perform the optimisation.

In [49], a protocol based conflict resolution method is considered where conflicts between three aircraft in the horizontal plane are resolved. The authors state that this can readily be extended to the N-aircraft case. The manoeuvres are restricted to heading changes.

The three dimensional conflict resolution problem is also tackled in [46], in which candidate manoeuvres include altitude, heading and speed change. A manoeuvre minimising a certain energy function is chosen from all conflict-free manoeuvres. A geometrical construction is proposed, solved via a numerical algorithm to determine the optimal manoeuvre for the two aircraft case. For the multi-aircraft case, an approximation is employed to compute a suboptimal two-legged solution. A similar approach is considered in [45], in which topological mapping considerations of the resolution manoeuvres are made. For encounters involving two aircraft, analytic expressions of the

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optimal solutions are obtained. For multiple conflict resolution, a convex optimisation technique is used to find the two-legged resolution manoeuvre in each manoeuvre type. As this becomes computationally intractable with increasing numbers of aircraft, a probabilistic resolution algorithm is used as a random solver to the combinatorial optimisation problem.

The resolution manoeuvres in [57] are investigated in both horizontal and vertical plane. The control is determined as a function of the relative motion state such that the range at closest approach is maximised. The solution is obtained by application of the Euler-Lagrange equations for optimal control. The study goes on to analyse the implementation of a conflict resolution and detection system, with the identification of possible sources of error and uncertainties.

An offline approach for solving planar conflict resolution is presented in [64]. This technique solves for a geometrical configuration of conflict avoidance regardless of the number of aircraft and their arrival patterns. The optimal space partitions are obtained via mixed integer programming. The aircraft modelling is purely kinematic, with simplifying assumptions ignoring mass and inertia parameters. The general scenario of three intersecting flows of aircraft is considered.

The objective in [60] is to select the most efficient manoeuvre from those with sufficiently high probabilities of being safe. The conflict resolution problem is formulated as one of a constrained optimisation. The problem is then approximated by posing an expected value criterion to be optimised in an unconstrained manner, with the constraint satisfaction encoded in the reward function. The expected value criterion is an expected value of some performance measure associated with the execution of the manoeuvre, with an appended reward for constraint satisfaction. The sequence of positions of the aircraft during the execution of the decision is a random variable whose distribution is dependent on the choice of manoeuvre. Maximisation of the expected objective yields a decision with maximum expected performance and high constraint satisfaction probability. The optimisation is performed via a Markov Chain Monte Carlo technique.

Finally, a human-in-the-loop CR algorithm is presented in FREER [24], where operations relevant to separation assurance in the Mid Term horizon are coordinated between Air and Ground. The algorithms used [35] emphasize on the way the situations are displayed to the controller, while providing him the possibility to easily manipulate trajectories.

4.3   Decentralisability

From the point of view of autonomous aircraft operations, an appealing attribute of any conflict resolution procedure would be ease of decentralisation of the technique. More promising in this context are cooperative approaches to decentralisation. We do not consider the noncooperative case

where aircraft intentionally withhold information.

Autonomous aircraft optimise their trajectories according to several factors including safety, weather, operating costs and coordination with other aircraft. Coordination between aircraft for conflict resolution yields benefits; the required magnitude of manoeuvering for a given aircraft may be reduced when two aircraft manoeuvre in a cooperative manner, rather than otherwise. Also, coordination could prevent manoeuvres being performed which could prolong or increase the degree of conflict. This could potentially increase the workload generated for the controller, but would be necessary in the airborne self separation setting. An agent-based decentralised approach involving negotiation between aircraft is adopted in [40], in which the extent of negotiation required to resolve conflicts is identified.

We make mention here also of the work in [66], which focuses on integrating solutions with the constraints of traffic flow management, including avoidance of airspace hazards and required times of arrival. Implementation considerations are also tackled in [4], and a method for switching to deploying future technologies and capabilities subject to economic constraints is outlined. As part of the broader aim of researching into automation capabilities to support autonomous aircraft capabilities, [55] details developments in the problem resolution function used to assist the en route sector controller team in handling the more complex traffic patterns which can arise from less structured autonomous aircraft concepts.

The project detailed in [34] provides a description of the current airborne surveillance situation, from both an airspace and aircraft perspective, through the analysis of European radar data recordings. An assessment of the possible operational benefits brought by the airborne surveillance applications being investigated is contained therein. The final report of the Mediterranean Free Flight Programme (MFF), [19], provides results and recommendations on Airborne Separation Assistance System applications obtained from a number of simulations, flight trial campaigns and paper reviews.

4.4 Concluding Remarks

A number of approaches to solving conflict detection and resolution have been proposed and have been reviewed here. A summary of these proposals, showing what kind of manoeuvres are considered, how multi-aircraft scenarios are handled, how aircraft trajectories are propagated (for conflict detection), and an estimate of the TRL, can be found in Table 2. Manoeuvre categories "Turns" and "Speed change" in Table 2 refer to resolution algorithms whose solutions consist of a small number of discrete decisions, as opposed to complete trajectories. We note that none of the approaches has a TRL higher than 2, in our estimation.

Approach	Dimensions	Manoeuvres	Multiple aircraft	Trajectory propagation	TRL
[16]	H	T	P	N	2
[38]	H	ST	G	N	2
[40]	?	?	?	?	2
[45]	H	CPT	G,P	N	2
[47]	HV	CPT	G,P	N	2
[49]	H	ST	G	P	2
[60]	HV	ST	G	P	2
[64]	H	ST	G	N	2
[70]	H	ST	?	P	2
[74, 75]	HV	ST	G	P	2

Table 2: Summary of Characteristics. **Abbreviations:** Dimensions: H = Horizontal, V = Vertical; Manoeuvres: T = Turns, S = Speed change, CPT = Continuous Piecewise Trajectory; Multiple aircraft: P = Pairwise, G = Global; Trajectory propagation: N = Nominal, P = Probabilistic.

5 Short Term Conflict Resolution

Short term Conflict Resolution in ATM is engaged when despite the actions taken in higher levels of CD&R, a conflict is about to happen. In general "short term" defines a time horizon of a few minutes; therefore it is obvious that the short term CD&R strategy is the last resort to avoid a conflict and ensure flight safety.

As discussed in Section 4, a conflict occurs whenever the protected zone of an aircraft is violated by another aircraft, i.e. when their distance becomes less than the radius of their protected zones. A potential conflict is detected whenever the trajectories of two aircraft are predicted to lead to a conflict in the future. This requires a mathematical model for the aircraft motion in order to make such a prediction. For a more detailed and formal definition of the Protected Zone and conflict the reader is referred to the paper [22] by Dowek and Munoz.

In current ATM practice the ATC is responsible for detecting and resolving conflicts within minutes (*Short Term Conflict Alert - STCA*), while the onboard crew, supported by automatic collision avoidance systems like *TCAS* [69] only acts to avoid imminent collisions that are just 1 minute or less away. The demands for a short-term CD&R system are different than higher levels: fast response as well as guaranteed performance are of upmost importance, while other criteria that apply to mid or long term collisions, like maintaining passenger comfort or minimizing fuel consumption and delay, are less important.

In the next section the currently used systems for airborne Collision Avoidance and ground short-term Conflict Avoidance, TCAS and STCA respectively, are presented, while reviews of Conflict Avoidance methods potentially suitable for short-term CD&R follow.

5.1 Traffic Alert and Collision Avoidance System - TCAS

The current industry standard for Collision Avoidance in ATM is TCAS - Traffic Alert and Collision Avoidance System. Development initiated in 1978, with TCAS II v.7 currently in use, while TCAS III is under development. A detailed presentation of the full characteristics of the system is given by FAA in [69].

TCAS in its present form is used as a supplementary system to inform the crew about possible collisions and instruct a vertical-only avoidance maneuver. As TCAS does not directly control the aircraft, the pilot has to decide whether to follow TCAS instructions and implement the instructed maneuver. The use of TCAS II v.7 is mandatory in Europe on aircraft with maximum take off weight of $5700kg$ or more, or a maximum passenger capacity greater that 19.

Collision detection by TCAS is realized using a projected time-to-collision

(tau) criterion. TCAS makes queries to nearby aircraft, using the existing mode S or mode C/A transponders (latest version requires mode S to be installed). During mode S operation unicast and broadcast queries are supported. Unicast queries are possible only to other mode S transponders and return the altitude of the aircraft replying, while the distance is estimated from the round-trip-time. Mode S transponders return the above information to broadcast queries too, while mode C/A (non-TCAS enabled) return a single "ping" reply, used to calculate the distance to them. Continuous tracking of up to 30 near-by aircraft is possible, and their relative velocities are estimated.

When a potential *intruder* i.e. a conflicting aircraft is detected a *Traffic Advisory* (TA) is issued to inform the onboard crew of the intruder's presence and prepare them for a possible maneuver. If a collision is imminent a *Resolution Advisory (RA)* is issued, which as explained before can be only vertical: "climb", "descend", "do not climb", "do not descend" etc, following predefined speed ranges. When both conflicting aircraft are equipped with TCAS coordination between them is done so that they both react in the best possible way. If the intruder does not have a functional TCAS system onboard the Resolution is non-coordinated. The latest TCAS versions allow for RA reversals while the resolution maneuver is in progress to better react to complex conflicting cases or uncoordinated intruders. In order for the ATC to have an overview of the resolution process, the RAs issued are automatically downlinked to the ground using the mode S transponder for as long as the resolution is in progress.

TCAS II has been designed to provide collision avoidance protection in the case of any two aircraft that are approaching horizontally at any rate up to 1200 knots and vertically up to 10,000 feet per minute (fpm). The maximum traffic density is about 0.3 aircraft per square nautical mile, which corresponds to 24 aircraft within a 5 nmi radius. For the case of a collision between just two aircraft a partial formal verification of the effectiveness of TCAS maneuvers has been possible by Livadas, Lygeros and Lynch [62]. It is important though to keep in mind that as its designers state, TCAS is not a flawless system: performance verification for a conflict between 3 or more aircraft if possible, has not been yet provided, while the maximum traffic density for safe operation is about to be reached in congested regions in the years to come. It is questionable whether using exclusively vertical maneuvers can offer the increased traffic capacity demanded for the future.

Nevertheless the experience obtained from its use up to now is very useful for further improvements on TCAS, as well as the developmental of novel methods for short-term CD&R.

5.2 Automatic Air Collision Avoidance System - Auto-ACAS

As explained above, the TCAS system issues Traffic Advisories (TAs) in advance of a potential collision so that the crew can act preemptively, causing "false positives" i.e. alerting the pilot when not necessary. This behavior can overload the pilot with undesired information, especially as the traffic density increases. To overcome this weakness Auto-ACAS [80] has been developed, initially with high performance military aircraft in mind.

Auto-ACAS is a decentralized but highly coordinated algorithm as it assumes constant exchange of information between neighboring aircraft. Apart from reducing "nuisance" (i.e. false alerts) Auto-ACAS has been designed to handle asynchronous operation between algorithms in different aircraft as well as delays up to about $0.3s$.

The main difference in principle between TCAS and Auto-ACAS is that the former system uses the projected (straight line) trajectory to detect a collision, while the latter constantly calculates a number of potential escape maneuvers (usually 3) which in combination with the aircraft size characteristics and minimum separation distance define the *claimed space*. Uncertainties in the aircraft's course are taken into account, thus forming an escape cone, which is then communicated between aircraft using a data link. Each aircraft examines whether there exists a possible collision between its escape cones and those of nearby aircraft obtained via the data link, as in Figure 2. If the cones are intersecting then an automatic escape maneuver is performed by Auto-ACAS in combination with the Flight Control System - FCS. On the contrary, when the escape cones are away from each other then the trajectory is stored as a safe escape maneuver.
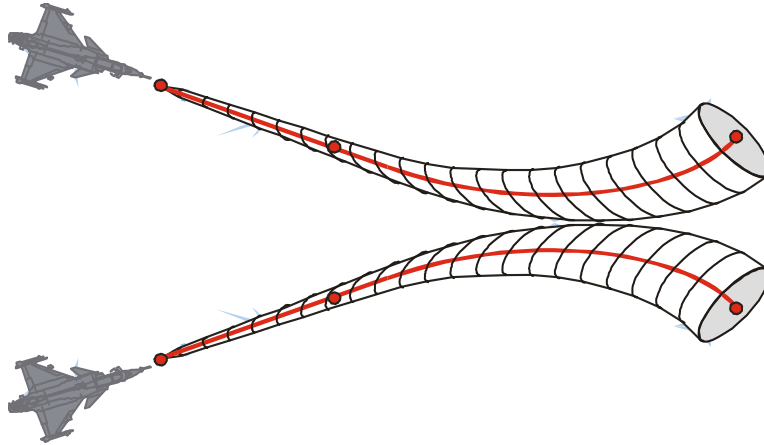

Figure 2: Collision Detection using predicted escape cones

By the above procedure an escape maneuver is initiated only when it is absolutely necessary, thus allowing the pilot to resolve a potential con-

flict/collision before Auto-ACAS is triggered. As the system is activated no sooner than the very last possible instant, nuisance is kept to a minimum. Moreover the level of uncertainty is minimized as the calculation of each aircraft's own escape maneuver using a known, predefined procedure is far more precise and reliable than the estimation of the probable trajectory of another aircraft.

The system includes provisions for failures in the operation of the system on nearby aircraft, or in the communication. Moreover navigation degradation is inherently taken into account while calculating the projected escape cone. In addition Auto-ACAS incorporates formation flying logic, which allows for safe close formation flights, while unnecessary activation during rejoining maneuvers is inhibited.

Although initially designed for high performance military aircraft, Auto-ACAS incorporates a priority class system with four classes defined (UAV, fighter, heavy, non-maneuvering in increasing priority) thus ensuring that an aircraft of a higher priority will have right of way over lower class neighbors.

Computer simulations, as well as flight tests have been conducted for Auto-ACAS. The results are quite encouraging shown Auto-ACAS to offer

In conclusion, Auto-ACAS offers significants improvements to TCAS, primarily because of the almost total elimination of nuisance. Equally important is the inherent handling of uncertainties: each aircraft has to predict its avoidance trajectory rather than perform some form of state propagation to derive a probable trajectory for neighboring aircraft. By this scheme kinematic constraints are easier to be implemented. Provisions for formation flight and priority classes are also important in some applications.

It should be noted though that Auto-ACAS, at least in its coordinated form presented above, assumes that each aircraft has the ability to predict it escape maneuver and that there is a data link available between aircraft so that constant communication of each others escape maneuvers is possible. Nonetheless the system can operate in non-coordinated mode without the exchange of escape maneuvers between aircraft, but then the probable trajectory has to be used instead, increasing the level of nuisance.

5.3   Ground Based Short-term CD&R - STCA

While the aforementioned TCAS and Auto-ACAS systems operate onboard each aircraft and beyond the conflict level, Short Term Conflict Alert is a ground based conflict detection system. Specifically it is used on the ATC stations in congested areas in order to provide warning and information to the controllers about possible conflicts.

As any system operating on the ATC level, STCA is centralized, in the sense that it continuously monitors all the aircraft in a sector and checks for potential conflicts between any two of them. STCA is more of a concept and set of specifications and operational requirements rather that a explicitly

defined system and thus its implementation can vary depending on the ATC provider. The requirements for STCA as described by EEC can be found in [37]. The general notion behind STCA is to draw the attention of the ATC to imminent conflicts so that he can resolve them in time. As each controller monitors a large number of aircraft, the level of nuisance must be low so that the controller is not overloaded with unnecessary alerts.

In order to predict the future trajectories of the aircraft and thus any possible losses of separation, surveillance data are used, specifically the aircraft ground speed, heading and rate of climb or descent are used, while no intent information is exploited. In addition the algorithm takes into account Cleared Flight Levels (CFL) and adapts accordingly the predicted trajectories. Measurement and prediction uncertainties are added to the trajectories so that a projected volume is calculated. In order to keep false alerts to a minimum, the probabilities of loss of vertical and lateral separation are combined so that the probability of conflict is estimated and used to determine whether each possible conflict will be shown to the ATC. The look-ahead time for STCA has been set to two minutes as this has been found to provide the optimum compromise between reliable prediction and minimization of false alerts.

As previously mentioned, STCA is merely a conflict prediction system that relies on the air traffic controller to asses the importance of each alert and issue resolution instructions to the corresponding aircraft. Therefore it is not a complete CD&R solution by itself, but a supporting tool. In the Autonomous Aircraft concept such a centralized system will probably not be necessary, since onboard equipment will handle Short Term CD&R, nevertheless it can remain as an extra safety feature in case of malfunctioning onboard systems or unequipped aircraft. An implementation of STCA is VERA [33] that is being used by Maastricht UAS (Upper Air-Space) by providing information to the controllers about any predicted conflicts, so that they can be resolved more efficiently. The latest operational version is described in [54], where a probabilistic model is used to improve the trade-off between the warning time and the rate of nuisance alerts.

5.4 CD&R using Optimization Methods and other existing methods

A wide variety of approaches to CD&R utilize optimization techniques in order to incorporate requirements such as minimum fuel consumption or deviation from planned course, and passenger comfort. Optimization offers a natural framework for dealing with such matters and has been adapted to various operational models. Conflict avoidance is expressed as an inequality constraint, usually of quadratic form, while a cost function representing delay, deviation from track or other fitness criteria is minimized.

Specifically in [84], [83] and [82] a worst case approach for 2 aircraft is

presented, where each one calculates the maximal set of initial conditions that guarantee a safe trajectory for the system for all possible maneuvers of the conflicting neighbor. This algorithm is inherently non-cooperative and decentralized and is mostly suited for off-line prediction of safe and unsafe escape maneuvers.

A less conservative, cooperative approach is developed in [8], [9] and [7]. Each aircraft is considered to have information on the state and goals of all other ones closer than a maximum "alert" distance and based on this knowledge designs its trajectory so that the sum of the delays of all neighboring aircraft is minimized, while avoiding conflicts.

Durand et al. [26] describe another distributed algorithm for short term conflict resolution, where prioritized planning is considered, planning new trajectories for aircraft after first establishing a priority order. Establishing an order of priority could also enable the distributed use of a "one against many" algorithm, like in [53].

A similar formulation of the problem described above is used in [65] and [52], in an even more decentralized form where each aircraft's cost function depends solely on its own trajectory. This last approach is the most promising. The authors assume a global system comprising of multiple local subsystems which interact through local constrains that are imposed on their states. A solution is then calculated by an algorithm involving Lagrange multipliers and penalty function methods which offers global convergence in a finite number of steps.

A class of CD&R methods using a different form of optimization include those proposed by Bilimoria [10] and Dowek, Munoz and Geser [23]. In these approaches the relative speed between conflicting aircraft is used to calculate the relative trajectory of the intruding aircraft. Note that no intent information is used, only position and velocity vector information are considered to be available. Once a loss of separation is detected, a family of new trajectories is produced that are tangential to the protected zone of the intruding aircraft, thus providing a separation equal to the minimum allowed. Specifically the new trajectories are designed by assuming a discrete maneuver (i.e. instantaneous change in heading, ground speed or both) strictly with geometric means and in a closed form. As there are infinite maneuvers that produce tangential trajectories, 3 types of solutions are considered as candidates: the ones given only by a heading or ground speed change, and those that require the least possible change in the velocity vector. The effectiveness of the algorithm presented in [23] has been formally verified by the authors in [22].

Last but not least, Hill et al. in [42] investigate a cooperative multi-agent approach for the autonomous navigation concept. Their approach is based on satisficing game theory, which enables the decision makers to take into consideration the preferences of others.

In general optimization methods for aircraft CDR are appealing for han-

dling constraints and performance requirements, but pose considerable difficulties for an application to short term CDR because of computational issues and combinatorial complexity for more than 2 aircraft.

An interesting approach that does not fall into the category of optimization-based methods is the one investigated within the FREER project [24], where an ASAS component for CR, acting up to 8 minutes ahead of TCAS, is used. There the idea is, instead of advising the pilots what to do to resolve a conflict, to advise them with what not to do. Thus, in this approach pilots remain the masters of the situation and not the automation tool. The solutions are calculated using a human-in-the-loop CR tool, namely HIPS [35].

5.5   Potential Field Methods

Although widely used for the motion control of mobile robots, methods using artificial potential fields have not yet been very popular in aircraft CD&R. This is due to the common inability of such methods to ensure bounded inputs that are feasible with respect to the aircraft performance. For an overview of various potential field methods to aircraft CD&R the reader is directed to reviews by Zeghal [90] and [91]. In the following we will present the work done by Kosecka, Tomlin, Pappas and Sastry in [56], as representative of the class of potential field methods.

The authors of [56] address the problem consisting of a number of aircraft, all flying in the same horizontal plane. Each aircraft i is surrounded by its protected zone, which is a circle of radius r_i around it. Current configuration of the aircraft is $q_i = (x_i, y_i)$ while its goal position is $q_{di} = (x_{di}, y_{di})$.

Each aircraft is guided under the combined action of forces created by a number of artificial potential fields:

- A field that is attractive towards the goal which is responsible for achieving convergence to the desired configuration:

$$U_a(q_i, q_d i) = \frac{1}{2} \|q_i - q_{di}\|^2 \tag{1}$$

The force generated by this field is calculated as usual:

$$F_\alpha(q_i, q_{di}) = -\nabla U_\alpha(q_i, q_{di}) = -(q_i - q_{di}) \tag{2}$$

- A repulsive field between each two aircraft i and j:

$$U_r(q_i, q_{di}) = \begin{cases} -\frac{1}{2\delta_{r_j}} \left(r_{ij} - (r_j + \delta_{r_j})\right)^2, & \text{if } r_j \leq r_{ij} \leq r_j + \delta_{r_j} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where by r_{ij} is denoted the distance between the two aircraft and δ_{r_j} is the "influence zone" (equivalent to the sensing radius used in other

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methods) of the repulsive field of aircraft j. The force created by this field is

$$F_r(q_i, q_j) = \nabla U_r(q_i, q_j) \tag{4}$$

and is responsible for conflict avoidance.

- The above two forces alone can lead to a deadlock during a perfectly symmetric encounter. This stagnation is avoided by the use of a vortex field around each aircraft, which creates the corresponding force:

$$F_v(q_i, q_j) = \pm \left[\begin{array}{c} \frac{\partial U_r(q_i, q_j)}{\partial y} \\ -\frac{\partial U_r(q_i, q_j)}{\partial x} \end{array} \right] \tag{5}$$

where in each $i - j$ pair the two different aircraft use opposite sign in F_v in order to head away from each other.

Finally the control law for aircraft i is formed as a dynamic model given by:

$$\dot{q}_i = \frac{F_\alpha(q_i, q_{d_i})}{||F_\alpha(q_i, q_{d_i})||} + \sum_i (k_{r_i} F_r(q_i, q_j) + k_{v_i} F_v(q_i, q_j)) \tag{6}$$

where k_{r_i}, k_{v_i} are adjustable gains. The algorithm as presented is of course decentralized and cooperative as it demands coordination between conflicting aircraft for the sign assignment of the Vortex force.

The authors then proceed to the application of the algorithm presented above to test cases of three generalized categories:*overtake* and *head-on* for two-aircraft encounters and *roundabout* for multiple aircraft encounters. The resulting trajectories dictated by the applied control scheme vary qualitatively with variations in the control gains. Although the trajectories for up to three aircraft encounters are proven by Ghosh and Tomlin to be kinematically safe [39], they are not always feasible with respect to aircraft kinematic constrains, while a proof for multiple aircraft is not available.

5.6   Navigation Functions

The Navigation Functions method is based on a potential field, which drives the agent/aircraft away from conflicts and towards the goal configuration. Rimon and Koditchek in [76] have introduced the methodology and currently it is being further developed in the Control Systems Lab of NTUA. Specifically the framework has been expanded and applied to the cases of multiple Non-Holonomic 2D Vehicles by Loizou, Dimarogonas and Kyriakopoulos [63], [79] and limited agent sensing. (This work has been done in the HYBRIDGE Project). A further expansion to the case of 3D non-holonomic vehicles is in progress. A decentralized approach has also been presented by Zavlanos in [89].

Navigation functions are real valued maps constructed using cost functions, whose negated gradient field is attractive towards the goal configuration and repulsive with respect to obstacles. The main features of the method are presented in the following paragraphs.

The problem treated in holonomic, planar applications is as follows: m mobile vehicles operate in a disc workspace $W \subset R^2$. Each vehicle R_i, $i = 1, ..., m$ occupies a disc in the workspace: $R_i = \{q \in R^2 : ||q - q_i|| \leq r_i$ where q_i is the center of each vehicle. The configuration of the vehicles is given by $q = \left[q_1^T, ..., q_m^T\right]^T$, and therefore the desired configuration is q_d. A navigation function is a map $\phi : F \to [0, 1]$, where $F \subset R^n$ is an analytic manifold with boundary that satisfies the following properties:

1. It is analytic on F,

2. It has only one minimum at $q_d \in \overset{o}{F}$ where $\overset{o}{F}$ denotes the interior of F,

3. Its Hessian at all critical points (zero gradient vector field) is full rank, and,

4. $\lim_{q \to \partial F} \phi(q) = 1$

The navigation function considered is

$$\phi = \sigma_d \circ \sigma \circ \widehat{\phi} = \left(\frac{\gamma}{\gamma + G}\right)^{1/k} \tag{7}$$

where $\sigma_d = x^{1/k}$, $\sigma = \frac{x}{1+x}$ and $\widehat{\phi} = \frac{\gamma}{G}$ the cost function. $\gamma^{-1}(0)$ is the desirable set, i.e. the goal configuration, and $G^{-1}(0)$ the set that must be avoided, i.e. conflicts between vehicles. The function G is by construction an indicator of proximity to conflicts, as it tends to zero when a conflict is imminent, and increases when the danger of any conflict is fading.

By using the above definition for ϕ (7), the set of critical points, as well as their (Morse) indices is identical between $\widehat{\phi}$ and ϕ. This facilitates the proof of the following propositions, as results for function ϕ can be derived by examining the simpler function $\widehat{\phi}$:

Proposition 1 *If the workspace is valid, the destination point q_d is a nondegenerate local minimum of ϕ.*

Proposition 2 *If the workspace is valid, all the critical points of ϕ are in the interior of the free space.*

Proposition 3 *For every $\epsilon > 0$ there exists a positive integer $N(\epsilon)$ such that if $k > N(\epsilon)$ then there are no critical points of $\widehat{\phi}$ in $F_1(\epsilon)$, where $F_1(\epsilon)$ denotes the set away from conflicts.*

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Proposition 4 *For any valid workspace, there exists an $\epsilon_0 > 0$ such that $\widehat{\phi}$ has no local minimum in $F_0(\epsilon)$, as long as $\epsilon < \epsilon_0$, where $F_0(\epsilon)$ denotes the set near conflicts.*

The complete proof for the above propositions can be found in [63] by Loizou and Kyriakopoulos.

The proposed control law is

$$u = -K\nabla\phi(q) \tag{8}$$

By the 4 propositions above it is then established that the goal configurations are achievable for all vehicles without any conflicts at the target. Furthermore, when away from the goal configuration, there is always a decreasing direction for the navigation function, and the control law drives each vehicle towards this direction. In conclusion, the convergence of all the vehicles to their respective target configurations is guaranteed, along with conflict avoidance during their motion.

Further work of Navigation Functions has led to application on decentralized problems, where each vehicle is not aware of the others' goals [89]. In this case the (decentralized) navigation function for vehicle i is:

$$\phi = \left(\frac{\gamma_d(q_i) + f\left(G(q)\right)}{\left(\gamma_d(q_i) + f\left(G(q)\right)\right)^k + G} \right)^{1/k} \tag{9}$$

where $\gamma_d(q_i) = ||q_i - q_id||^2$ is the squared metric of vehicle's i current configuration q_i from its goal q_{id}.

The function $f\left(G(q)\right)$ is responsible for the cooperation between neighboring vehicles, by forcing all agents to keep a minimum distance between them so that each of them has some margin available for movement and stagnation of the system is avoided.

Navigation functions have been also used by Dimarogonas and Kyriakopoulos for the control of vehicles with limited sensing capabilities, i.e. where each vehicle has knowledge only of the position of other vehicles within a maximum sensing distance [21].

Another interesting extension of the navigation function methodology is the application to non-holonomic vehicles, specifically unicycle-type planar vehicles [63]. The main modifications in this approach are the use of a *Dipolar Navigation Function* and the use of a different control law, which is compatible with the unicycle model of motion.

A Dipolar Navigation Function is given by

$$V = \frac{\gamma_d(q_i)}{\left(\gamma_d(q_i)^k + H_{nh}(q_i) \cdot G \cdot \beta_0\right)^{1/k}} \tag{10}$$

The term $H_{nh}(q_i)$ is what makes the potential field dipolar. It is used as an artificial obstacle, which is in fact the plane whose normal vector is parallel

to the desired alignment. This addition to the Navigation Function makes all the trajectories converging to the goal position while being parallel to the desired configuration. This ensures that the trajectory is feasible for the non-holonomic vehicle and that no in-place rotation will be needed. An example field of a dipolar navigation function is presented in Figure 3.
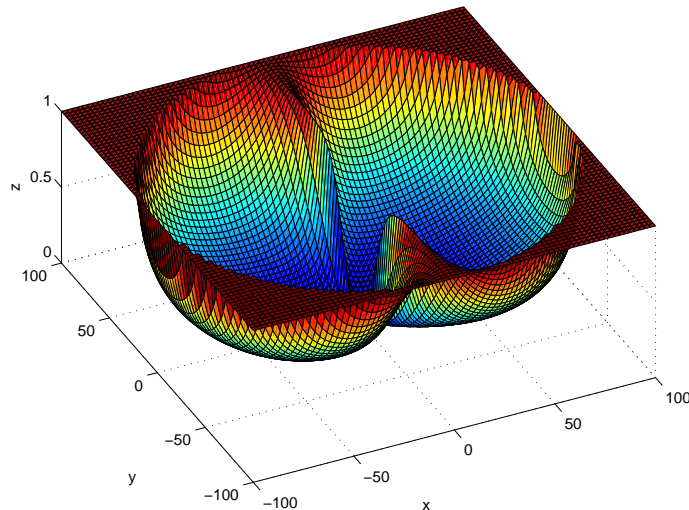

Figure 3: A Dipolar Navigation Function

Current research in the Control Systems Lab within the iFLY project includes the expansion of the Navigation Functions Framework to address systems of 3D non-holonomic vehicles, which better represent aircraft.

Concluding, Navigation Functions have already demonstrated efficient mobile vehicle motion control, with guaranteed conflict avoidance and convergence to the goal configuration being key characteristics, especially for short-term CD&R. Although initially used for mobile robot navigation, continuing adaptations to problems that resemble better ATM have been presented, while research is in progress.

Navigation Functions have the ability to operate in a decentralized manner, so they can be used for the A^3 concept. In addition the feedback nature of the method makes it fast and robust with respect to modeling and measurement uncertainties.

Further research will address the kinematic constrains imposed on aircraft (passenger comfort, aircraft performance etc.) as well as an extension to the case of 3D moving aircraft, as explained above.

5.7 General Conclusions on Short Term CD&R

TCAS is now an established standard for Collision Avoidance, and although acting one level below CD&R, it can provide valuable feedback for any CD&R method working above it. In addition, since it is already in use it can be a useful reference in terms of performance, functionality and integration with the existing and future aircraft technology, as well as pilot and ground ATC operations.

In order to achieve fast and guaranteed short-term conflict avoidance in a high density traffic environment new approaches need to be considered. Of the frameworks mentioned above reactive methods are the most appealing since they offer robustness, fast response and their performance can be guaranteed when properly formulated, like in Navigation Functions. Of course the input constraints imposed on aircraft will have to be taken into account, as it has been recognized through the HYBRIDGE project.

In the concept of Autonomous Aircraft that maintain their own separation it is useful to use some form of prioritization and right of way. This is particularly important in the case where a mixed traffic comprising of many different aircraft classes is considered, like autonomous and ground controlled aircraft or airliners and general aviation (and potentially UAVs in the future) use the same airspace. The enforcement of a reliable priority system can ensure that certain types of aircraft can have right of way, i.e. they will plan their trajectories without taking conflicts with lower-priority aircraft into account and force them to maneuver first in order to avoid a conflict. Such a priority rule is implemented in TCAS and provides some form of coordination between conflicting aircraft. Using a limited sensing radius though makes the establishment of a global priority rule quite difficult. The problem has been addressed in an effective way by Alliot, Durand and Granger in [25].

Protocols like Auto-ACAS could also provide a useful way to maybe combine a number of different underlying algorithms so that the best maneuver can be selected, though a less conservative scheme would obviously have to be used to civil aircraft. The reduced false positives that result from such an approach will be very welcome in a congested airspace where a large number of probable conflicts will arise at any given moment, but only a part of them will actually demand immediate resolution.

6 Centralized vs. Decentralized Approaches

6.1 Introduction

In principle Conflict Detection and Resolution methods can be classified in *Centralized* and *Decentralized*, depending on whether the responsibility for maintaining separation falls on a single global controller, or is distributed to all the agents. In essence the factors that determine whether a strategy is considered Centralized or Decentralized are *Global Knowledge* and *Objectives*: in strictly centralized strategies a single controller has complete knowledge about all the agents and full control on them in order to achieve a single objective, while in completely decentralized methods each agent has limited knowledge of other agents and aims to achieve a unique for each agent objective. Of course the above discrimination is not always strict, as there can be varying levels of global knowledge and difference in objectives between agents. A more extensive classification of CD&R methods has been presented by Dowek and Munoz in [22].

In the case of a decentralized strategy, a further classification is possible depending on the relation between objectives of different agents. Contradicting objectives as well as absence of any coordination between different agents characterize a control strategy as *Non-cooperative* or *Competitive*, while non-contradicting objectives or coordinated actions define a *Cooperative* strategy. A typical example of a non-cooperative scheme is the evasion and pursuit problem, while conflict avoidance between two aircraft is in principle cooperative.

6.2 Decentralization

The distribution of the responsibility for CD&R from a single controller to the individual agents offers a number of advantages. Most importantly it reduces or even eliminates the need for a complicated global controller. As the population of interacting agents increases, the number of possible conflicts that a global controller would have to detect and resolve grows rapidly, while in the decentralized scheme growth tends to be slower, thus requiring less effort by each agent. In addition, as verified by experimental results [8] decentralized strategies tend to result in more robust behavior while centralized methods are less fault tolerant since an malfunctioning global controller affects the complete system of agents.

Despite the disadvantages mentioned above, centralized approaches generally result in globally optimal solutions that take into account all the information available in the system. On the contrary decentralized methods can only produce locally optimal solutions, since each agent has access only to local information of the system and aims to satisfy a different, local objective.

6.3 Decentralization in ATM and Autonomous Aircraft Concepts

Specifically in the ATM problem the information an aircraft can have about others in its environment is:

- presence

- position

- velocity vector

- intent - (eg. destination, desired path)

Specifically the intent information is of great importance, because in practice all other information about an aircraft's neighbors can be obtained through surveillance, while intent information has to be actively broadcasted by each aircraft. Thus the use of 4D information for CD&R requires a fundamental change in the communication between aircraft. Of course providing intent information can offer more accurate and reliable prediction of potential conflicts, along with more efficient resolution maneuvers. The current ATM strategy, as implemented by the ground ATC, is centralized, as the ATC alone has complete knowledge for each aircraft in his sector, and is responsible for maintaining the required separation between all of them. In contrast, the safety collision detection and resolution system TCAS, as described by FAA in [69] is mainly decentralized as each aircraft has knowledge only of the position and velocity of its neighbors. As explained in Chapter 5, the TCAS system can operate with or without coordination between conflicting aircraft, and even when only one aircraft is equipped with it, therefore it cannot be classified strictly as a cooperative or non-cooperative strategy.

Decentralized CD&R algorithms for ATM usually assume that each aircraft has limited knowledge about its neighbors, i.e. it can detect other aircraft in a area around it, estimate their position, and maybe their velocity vector. The maximum sense radius defines the *Alert Zone* and is a tuning parameter for decentralization: a small radius implies local sensing, while a large one makes the approach closer to being centralized (e.g. ATC would still have access to more info than TCAS, flight plans, weather etc). For a further comparative analysis of Centralized and Decentralized CD&R methods in ATM the reader is referred to [58] by Krozel, Peters and Hunter [NASA].

The *Autonomous Aircraft Concept* and A^3 assumes autonomous aircraft, that use a decentralized control strategy and rely only on local information in order to avoid and resolve conflicts. The A^3 concept refinement, intended to investigate how A^3 equipped aircraft can be integrated with the SESAR concept in order to further increase capacity, may include some form of

supporting centralized control. As pointed out by Hoekstra and Ruigrok in [43], decentralized methods are more appropriate for local, short-term problems like en-route separation and optimal flight planning (for a single aircraft) while problems that involve a large number of aircraft (eg traffic flow management) or shared resources (e.g. a congested corridor or a busy airport) demand a centralized approach. This has been obvious in the previous chapters, as Long-term CD&R uses centralized algorithms (CFMU) while a decentralized system is used as a last resort for Short-term conflicts.

Some of the mid-term conflict resolution algorithms reviewed in chapter 4 could be implemented in a decentralized manner to some extent. However they all assume some knowledge of the intent of other aircraft, and thus are all reliant on communications being in place between aircraft, and between aircraft and ground.

Resolution algorithms which are intended for decentralized on-board implementation, but with unbroken communications, are those described in [16, 40].

The algorithms described in [49, 50] find resolution manoeuvres which conform to pre-specified protocols. This gives them some resilience to interruptions in inter-aircraft communications, although they still rely on communications to establish initial states and intentions of other aircraft, and presumably some updates of these in complex scenarios. Also [64] describes an approach which requires initial state information only at the boundary of a "control volume".

The remaining algorithms reviewed in chapter 4 are conceived as centralized algorithms, though some of them may be amenable to some degree of decentralization, for example by distributing the computational task involved. Further study is needed to establish the extent of these possibilities.

Concerning Long Term CD&R, as already discussed in Section 3, the problem is mainly formulated as a traffic flow management problem. These kinds of problems are difficult to solve decentralized in the flying agents, since they involve more strategic decisions for the system over horizons far larger than the average aircraft flight time. For all the Long Term CD&R algorithms, global knowledge is of great importance, while aircraft exact positions and velocities are not needed as the planning takes place prior to a flight. Finally, it has been clear in Section 3 that Long Term CD&R algorithms are the most computational intensive algorithms and aim at the global optimal solution for the system, making decentralization difficult for this problem.

The integration of the three CD&R levels in a complete system with decisions made locally (onboard) as well as globally (ground ATC) is of great importance. The interfacing between adjacent levels, i.e. between Short and Mid term, and between Mid and Long term must be efficient and assure safety. An approach for the integration of Short and Mid term levels has been proposed in [14, 77] where Decentralized Navigation Functions are

used in the Short Term level to ensure flight safety, while Model Predictive Control is used in a higher, centralized level to update periodically the destinations used by Navigation Functions in order to perform higher level planning, avoid infeasible maneuvers and optimize the resulting trajectories with respect to various performance criteria. Another relevant research is currently in progress by NASA Research Centers. In their work they consider mid to short term conflict resolution, trying to maximize flexibility for all aircraft for the mid term horizon, while using genetic algorithms over some predefined resolution maneuvers for the short term conflict resolution. Some preliminary results of this research can be found in [51], [17].

7 Enabling Technologies

CD&R Enabling technologies can be split into two groups:

1. Technologies that provide input information to the CD&R application,

2. Technologies that ensure a proper execution of the CR maneuvers.

7.1 Information Providing Technologies

The availability of updated traffic information is a basic enabler of any ATM related application. This information should be for shorter distances provided through direct Air-Air data link communication via Automatic Dependent Surveillance Broadcast/Contract (ADS-B/C).

While the range of ADS-B channels seems to be rather limited (see results of CASCADE project [31]), information sharing should be largely provided by the System Wide Information Management (SWIM). SWIM is a communication architecture that is planned to allow the exchange of data across the whole European ATM system by the integration of Air-Ground and Ground-Ground data and ATM services exchange [32].

The information about a flight will be broadcast through ADS-B in the form of different messages: state messages with high update frequency, and intent messages with lower update rates.

7.1.1 Intent Description

The uncertainty envelope around the intended path is strongly dependent on the source and status of the trajectory description. The guidance of aircraft is not an open-loop process and automated flight (FMS managed modes) is performed along the trajectory generated by, and stored in, the on-board Flight Management System (FMS). If this airborne trajectory, used by the aircraft guidance system, is transmitted and used by ATM applications, the uncertainty envelope may be considerably reduced. Furthermore, advanced navigation approaches as part of Performance Based Navigation provides a unified way to provide reliable information regarding this uncertainty.

An alternative approach to the construction of a predicted trajectory, often used by ground systems, is the transmission of a more limited set of information and the use of a ground-based trajectory predictor. This approach is more computationally demanding and less accurate than FMS predicted trajectories (this is primarily due to more accurate aircraft performance models, stored in the FMS, as compared to ground-based performance models, such as BADA [30]). Other factors impacting trajectory prediction accuracy are forecasted weather data, locally sensed weather data, and aircraft state date (such as gross weight). The ground-based systems have access to the first, while the aircraft has better knowledge of the second and third factor. The advantage of this approach is less demanding communication.

7.1.2   Sensors

Besides the information about hazards provided by SWIM or through direct Air-Air communication, airborne sensors such as a weather radar, and a ground proximity warning system may be used to provide the additional data for the CR algorithm.

7.2   Guidance system – CR Maneuvers Execution

In principle, there are two alternatives to performing CR maneuvers using an automated aircraft control:

1. Using the FMS by specifying an additional waypoint/constraint within the current flight plan,

2. Using the autopilot by setting up a new guidance target (heading, altitude, etc.)

Within the ASAS related literature these two possibilities are referred to as the intent-based (FMS) and the state-based (autopilot) conflict resolution (the INTENT project [18], Mediterranean Free Flight [19]). Very often these variants of the CR are linked to the availability of the intent information to the CD module, although there is not a direct correspondence.

In fact, as the own intent is always available in the FMS, both types of CR can be used independently on the information considered by the CD module and for the same purposes. For example, the track angle can be always changed either directly on the flight mode panel or by specifying a suitable additional waypoint in the flight plan. The FMS based solution should be in general preferable as it corresponds to optimized execution of the maneuver and the FMS automatically considers the needed speed changes to meet the applicable time constraints. Thus user preferences can be maintained and stakeholder benefits realized. The minor drawback of this choice is some delay before the maneuver execution (the autopilot mode should be used when a potential conflict is already very close).

Taking these two possibilities of maneuver execution into account during the design of the CR algorithm allows us to benefit from the capabilities of modern FMS and develop a more effective ASAS system.

7.3   Existing Avionics Systems and CD&R

Within current avionics systems, the Traffic Collision Avoidance System (TCAS), discussed in the Section 5, is the only airborne system providing a resolution function. It is supposed to work as an independent safety backup for future ASAS applications as it is based on the Mode-S state information, not on information gathered by data link.

In addition, the CR optimization process can benefit from performance optimization that is currently performed by the FMS (in fact, it was the reason why the FMS was invented) using algorithms that balance the optimization between fuel costs and desired timing. There is actually no airborne system for optimized lateral rerouting as this flexibility is not available in the current ATM system. The FMS has an accurate, OEM-defined aircraft performance model, it can handle weather forecast along the planned trajectory, and allows the effective guidance of the aircraft along the predicted path while meeting both spatial and time constraints. In this context, FMS is a good candidate for implementing the newly required ASAS functionality.

8 Conclusion

The most important methods in conflict resolution have been reviewed and analyzed in terms of their capabilities, limitations and complementarities from a general autonomous aircraft conflict resolution perspective. Advantages and disadvantages of various CD&R methods have been identified, focusing on the applicability with the relevant A^3 concept, as well some possible concept refinements that will be investigated within iFly. The CD&R methods have been reviewed according to their corresponding time horizons and have been classified as Long-Term (Traffic Flow Management) methods (for horizons longer than an hour), Mid-Term methods (for horizons of tens of minutes) and Short-Term methods (for horizons of minutes). The technological issues regarding the applicability of the CD&R methods have also been investigated, providing some more insight on how these methods can be implemented in the context of an autonomous aircraft concept.

From this comparative study and analysis of CD&R methods, it has become clear that the decentralizability of the algorithms is heavily dependent on the horizon over which CD&R is carried out. Specifically, long term CD&R methods cannot (in general) be applied in a decentralized manner, because of the global knowledge required, as well as the fact that usually they concern horizons much longer than typical aircraft flight times and might also involve techniques that are ground-based (e.g. ground holding). Trajectory management and weather avoidance though are two parts of long long term CD&R that have a potential to be applied in a distributed fashion. Things seem to be a bit more complicated on the mid term horizon, where some algorithms have been proposed in the literature for decentralized CD&R, though most of the times some knowledge of the states and intent of all other aircraft (which can be very far away) is assumed to be known, and thus are all reliant on communications being in place between aircraft (and in some cases between aircraft and ground). Finally, in short term CD&R methods, decentralized algorithms are usually used, as they are the last resort for conflict avoidance between aircraft. In this case communication aspects are also very important, since state and intent knowledge of other aircraft is needed in several algorithms for the resolution to take place.

The role of D5.1 was to provide a summary of existing methods with a view toward application to A^3 concept of iFly and its integration with the SESAR concept, to be investigated in WP8. No major problems that require WP5 or any other iFly WP to change course have been identified. Several methods exist at all levels of CD&R hierarchy which, though not necessarily directly applicable to the iFly concept, could be adapted for this purpose. One shortcoming we have been able to identify in the literature is the lack of integrated methods that cover adequately more than one level of the CD&R hierarchy. Development of novel integration methods for mid

and short term CD&R is required for this purpose. As foreseen in the DoW, we will address this issue under the following task WP5.3.

In the next step of WP5, the conflict resolution requirements imposed by the ATM concept developed in WP1 and WP2 will be identified. It will be also important to understand the resources that the concept can make available for the CD&R tasks, in terms of communication, computation, etc. Once these are identified, the conflict resolution methods presented in this deliverable will be compared against these requirements in order to identify the most applicable methods for the iFly concept in each conflict resolution horizon. Furthermore, the coupling of these three different levels of CD&R in the iFly concept of A^3 has to be investigated. D5.1 will be the basic input to these tasks, along with the work carried out in WP1 and WP2; the results will be documented in deliverable D5.2.

References

[1] G. Andreatta and L. Brunetta. Multiairport ground holding problem: A computational evaluation of exact algorithms. *Operations Research*, 46(1):57–64, 1998.

[2] G. Andreatta, L. Brunetta, and G. Guastalla. Multi-airport ground holding problem: A heuristic approach based on priority rules. *Modeling and Simulation in Air Traffic Management*, pages 71–89, 1997.

[3] G. Andreatta, L. Brunetta, and G. Guastalla. Solving the multi-airport ground holding problem. *Annals of Operations Research*, 81:271–288, 1998.

[4] T.A. Becher, D.R. Barker, and A.P. Smith. Near-to-mid term solution for efficient merging of aircraft on uncoordinated terminal RNAV routes. Technical report, The MITRE corporation, February, 2005. URL `http://www.mitre.org/work/tech_papers/tech_papers_05/05_0123/`.

[5] D. Bertsimas and A. Odoni. A critical survey of optimization models for tactical and strategic aspects of air traffic flow management. Technical report, NASA Ames Research Center, 1997.

[6] D. Bertsimas and S. Stock Patterson. The air traffic flow management problem with enroute capacities. *Operations Research*, 46:406–422, 1998.

[7] A. Bicchi. An experimental study of performance and fault-tolerance of a hybrid free-flight control scheme. *Robustness in Identification and Control*, 1999.

[8] A. Bicchi and L. Pallottino. On optimal cooperative conflict resolution for air traffic management systems. *IEEE Transactions on Intelligent Transportation Systems*, 1(4):221–231, 2000.

[9] A. Bicchi, A. Marigo, G. Pappas, M. Prandini, G. Parlangeli, C.J. Tomlin, and S.S. Sastry. Decentalized Air Traffic Management Systems: Performance and Fault Tolerance. *Proceedings of the IFAC International Workshop on Motion Control*, 1998.

[10] K. D. Bilimoria. A geometric optimization approach to aircraft conflict resolution. *AIAA Guidance, Navigation, and Control Conference and Exhibit, Denver*, 2000.

[11] E. Boyd, R. Burlingame, and K. Lindsay. An algorithm for the management of national air traffic. Technical Report INEN/OR/WP/10/5-94, Texas A&M University, Texas, USA, 1994.

[12] R. Burlingame, E. Boyd, and K. Lindsay. *Solving Large Integer Programs Arising from Air Traffic Flow Problems*, pages 215–226. Kluwer Academic Publishers, Boston, MA, 1995.

[13] G. Chaloulos and J. Lygeros. Effect of wind correlation on aircraft conflict probability. *AIAA Journal of Guidance, Control and Dynamics*, 30(6):1742–1752, 2007.

[14] G. Chaloulos, G. P. Roussos, J. Lygeros, and K. J. Kyriakopoulos. Ground assisted conflict resolution in self-separation airspace. *AIAA Guidance, Navigation and Control Conference and Exhibit*, 2008. to appear.

[15] E. Chang, R. Hu, D. Lai, R. Li, Q. Scott, and T. Tyan. The story of mode s, 2000. URL `http://mit.edu/6.933/www/Fall2000/mode-s/mode-s.pdf`.

[16] J. C. Clements. Optimal Simultaneous Pairwise Conflict Resolution Maneuvers in Air Traffic Management. *AIAA Journal of Guidance, Control, and Dynamics*, 25(4):815–818, 2002.

[17] M.C. Consiglio, S.T. Hoadley, D.J. Wing, and B.T. Baxley. Safety Performance of Airborne Separation: Preliminary Baseline Testing. In 7th *AIAA Aviation, Technology, Integration, and Operations Conference (ATIO)*, 2007.

[18] INTENT consortium. INTENT: The Transition towards Global Air and Ground Collaboration in Traffic Separation Assurance. Technical report, 2001-03. URL `http://www.intentproject.org/`.

[19] MFF consortium. MFF: Mediterranean Free Flight. Technical report, 2005. URL http://www.medff.it/public/index.asp.

[20] A. d'Aspremont, D. Sohier, A. Nilim, L. El Ghaoui, and V. Duong. Optimal path planning for air traffic flow management under stochastic weather and capacity constraints. *International Conference on Research, Innovation and Vision for the Future*, 2006.

[21] D. V. Dimarogonas and K. J. Kyriakopoulos. Decentralized stabilization and collision avoidance of multiple air vehicles with limited sensing capabilities. *Proceedings of the 2005 American Control Conference*, pages 4667–4772, 2005.

[22] G. Dowek and C. Munoz. Conflict detection and resolution for 1,2,...n aircraft. 7th *AIAA Aviation technology, Integration and Operations Conference (ATIO)*, 2007.

[23] G. Dowek, C. Munoz, and A. Geser. Tactical conflict detection and resolution in a 3-d airspace. *Technical Report NASA/CR-*, 2001.

[24] VN Duong and EG Hoffman. Conflict Resolution Advisory Service in autonomous aircraft operations. *Digital Avionics Systems Conference, 1997. 16th DASC., AIAA/IEEE*, 2, 1997.

[25] N. Durand, J.-M. Alliot, and G. Granger. Faces: a free flight autonomous and coordinated embarked solver. In *ATC Quarterly*, 2000.

[26] N. Durand, J.-M. Alliot, and G. Granger. FACES: a free flight autonomous and coordinated embarked solver. In *ATC Quarterly*, 2000.

[27] L. Epstein, A. Futer, and L. Medvedovsky. Multiple airport scheduling. Technical report, Volpe National Transportation Systems Center, Cambridge, MA, USA, 1992.

[28] Eurocontrol. ATFCM users manual for CFMU, . URL http://www.cfmu.eurocontrol.int/cfmu/gallery/content/public/userdocs/docs/ATFCM_Users_Manual_Edition_12.pdf.

[29] Eurocontrol. Central Flow Management Unit (CFMU), . URL http://www.cfmu.eurocontrol.int/cfmu/public/subsite_homepage/homepage.html.

[30] Eurocontrol. The BADA project, . URL http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html.

[31] Eurocontrol. The CASCADE programme, . URL http://www.eurocontrol.int/cascade/public/subsite_homepage/homepage.html.

[32] Eurocontrol. The SESAR programme, . URL `http://www.eurocontrol.int/sesar/public/subsite_homepage/homepage.html`.

[33] Eurocontrol. Towards a controller-based conflict resolution tool - a literature review. 2002. URL `http://www.eurocontrol.int/eatm/gallery/content/public/library/litreview.pdf`.

[34] Eurocontrol. FALBALA Project Dissemination Forum. Technical report, Eurocontrol Experimental Centre, 2003-04. URL `http://www.eurocontrol.int/care-asas/public/standard_page/activities_4_falbala_diss.html`.

[35] Eurocontrol. PHARE Highly Interactive Problem Solver (HIPS). Technical Report 273/94, Eurocontrol Experimental Centre, November 2004.

[36] Eurocontrol. User manual for the base of aircraft data (BADA), 2004.

[37] Eurocontrol. Specification for short term conflict alert. 2006.

[38] E. Frazzoli, Z.H. Mao, J.H. Oh, and E. Feron. Aircraft conflict resolution via semi-definite programming. *AIAA Journal of Guidance, Control, and Dynamics*, 24(1):79–86, 2001.

[39] R. Ghosh and C.J. Tomlin. Maneuver design for multiple aircraft conflict resolution. *Proceedings of the American Control Conference*, 2000.

[40] K.A. Harper, S.L. Guarino, A. White, M.L. Hanson, K.D. Bilimoria, and D. Mulfinger. An agent-base approach to aircraft conflict resolution with constraints. *AIAA Guidance, Navigation, and Control Conference and Exhibit*, (AIAA 2002-4552), 2002.

[41] M. P. Helme. Reducing air traffic delay in a space-time network. In *IEEE International Conference on Systems, Man and Cybernetics*, pages 236–242, Chicago, 1992.

[42] J.C. Hill, F.R. Johnson, J.K. Archibald, R.L. Frost, and W.C. Stirling. A Cooperative multi-agent approach to free flight. In 4th *International Joint Conference on Autonomous Agents and Multiagent Systems*, pages 1083–1090. ACM Press New York, NY, USA, 2005.

[43] J.M. Hoekstra and R.C.J. Ruigrok. Topics in free flight research. In *ATCA/FAA/NASA symposium*, Atlantic City, 2005.

[44] R. Hoffman and M. Ball. A comparison of formulations for the single-airport ground-holding problem with banking constraints. *Operations Research*, 48(4):578–590, July 2000.

[45] J. Hu, M. Prandini, and S. Sastry. Optimal maneuver for multiple aircraft conflict resolution: A braid point of view. In *Proceedings of the IEEE Conference on Decision and Control, (Sydney)*, December 2000.

[46] J. Hu, M. Prandini, A. Nilim, and S. Sastry. Optimal coordinated maneuvres for three dimenstional aircraft conflict resolution. *American Institute of Aeronautics and Astronautics*, 2001.

[47] J. Hu, M. Prandini, and S. Sastry. Optimal Coordinated Maneuvers for Three-Dimensional Aircraft Conflict Resolution. *AIAA Journal of Guidance, Control and Dynamics*, 25(5), 2002.

[48] J. Hu, M. Prandini, , and S. Sastry. Aircraft conflict prediction in the presence of a spatially correlated wind field. *IEEE Transactions on Intelligent Transportation Systems*, 6(3), 2005.

[49] I. Hwang and C.J. Tomlin. Protocol based conflict resolution for air traffic control. Technical report, Dep. of Aeronautics and Astronautics, Stanford University, 2001.

[50] I. Hwang, J. Kim, and C. Tomlin. Protocol-based conflict resolution for air traffic control. *Air Traffic Control Quarterly*, 2007. (to appear).

[51] H. Idris, D.J. Wing, R. Vivona, and J.L. Garcia-Chico. A Distributed Trajectory-Oriented Approach to Managing Traffic Complexity. In 7th *AIAA Aviation, Technology, Integration, and Operations Conference (ATIO)*, 2007.

[52] G. Inalhan, D.M. Stipanovic, and C.J. Tomlin. Decentralized optimization, with application to multiple aircraft coordination. *Proceedings of the 41st Conference on Decision and Control*, 2002.

[53] R. Irvine. The GEARS Conflict Resolution Algorithm. *AIAA Guidance, Navigation and Control Conference*, 1998.

[54] M. Janssen. A new short-term conflict alert for the eurocontrol maastricht uac primary and fallback systems. *Skyway*, (43):38–39, 2006.

[55] D.B. Kirk, W.S. Heagy, and M.J. Yablonski. Problem resolution support for free flight operations. *IEEE Transactions on Intelligent Transportation Systems*, 2(2):72–80, 2001.

[56] J. Kosecka, C.J. Tomlin, G. Pappas, and S.S. Sastry. Generation of conflict resolution maneuvers for air traffic management. *Proceedings of the IEEE Conference on Intelligent Robots and Systems*, 1997.

[57] J. Krozel, M.E. Peters, and G. Hunter. Conflict detection and resolution for future air transportation management. Technical Report TR 97138-01, Seagull Technology, Inc., 1997. Prepared for NASA Ames.

[58] J. Krozel, M. Peters, K.D. Bilimoria, C. Lee, and J.S.B. Mitchell. System performance characteristics of centralized and decentralized air traffic separation strategies. *4^{t}h USAEurope Air Traffic Management R&D Seminar*, 2001.

[59] J.K. Kuchar and L.C. Yang. A review of conflict detection and resolution methods. *IEEE Transactions on Intelligent Transportation Systems*, 1(4):179–189, 2000.

[60] A. Lecchini-Visintini, W. Glover, J. Lygeros, and J. M. Maciejowski. Monte Carlo Optimization for Conflict Resolution in Air Traffic Control. *IEEE Transactions on Intelligent Transportation Systems*, 7(4): 470–482, 2006.

[61] K. Lindsay, E. Boyd, and R. Burlingame. Traffic flow management modeling with the time assignment model. *Air Traffic Control Quarterly*, 1 (3):255–276, 1993.

[62] C. Livadas, J. Lygeros, and N. Lynch. High-Level Modeling and Analysis of the Traffic Alert and Collision Avoidance System (TCAS). *Proceedings of IEEE*, 88:926–948, 2000.

[63] S. Loizou and K. Kyriakopoulos. Closed loop navigation for multiple non - holonomic vehicles. *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 4240–4245, 2003.

[64] Z. H. Mao, D. Dugail, and E. Feron. Space partition for conflict resolution of intersecting flows of mobile agents. *IEEE Transactions on Intelligent Transportation Systems*, 8(3):512–527, Sept. 2007.

[65] P.K. Menon, G.D. Sweriduk, and B. Sridhar. Optimal strategies for free flight air traffic conflict resolution. *Journal of Guidance, Control and Dynamics*, 1999.

[66] K.T. Mueller, D.R. Schleicher, and K.D. Bilimoria. Conflict detection and resolution with traffic flow constraints. *AIAA Guidance, Navigation, and Control Conference and Exhibit*, (AIAA 2002-4445), 2002.

[67] L. Navazio and G. Romanin-Jacur. The multiple connections multi-airport ground holding problem: Models and algorithms. *Transportation Science*, 32(3):268–276, 1998.

[68] A. Nilim and L. El Ghaoui. Algorithms for air traffic flow management under stochastic environments. In *American Control Conference*, 2004.

[69] U.S. Department of Transportation Federal Aviation Administration. Introduction to TCAS II version 7. 2000.

[70] R. A. Paielli. Modeling Maneuver Dynamics in Air Traffic Conflict Resolution. *AIAA Journal of Guidance, Control, and Dynamics*, 26 (3):407–415, 2003.

[71] R.A. Paielli and H. Erzberger. Conflict Probability Estimation for Free Flight. *AIAA Journal of Guidance, Control, and Dynamics*, 20(3), 1997.

[72] R.A. Paielli and H. Erzberger. Conflict Probability Estimation Generalized to Non-level Flight. *Air Traffic Control Quarterly*, 7(3), 1999.

[73] W. Philipp and F. Gainche. *Air Traffic Flow Management in Europe*, pages 64–106. Springer-Verlag, 1994.

[74] A. U. Raghunathan, V. Gopal, D. Subramanian, L. T. Biegler, and T. Samad. Dynamic Optimization Strategies for Three-Dimensional Conflict Resolution of Multiple Aircraft. *Journal of Guidance, Control, and Dynamics*, 27(4):586–594, 2004.

[75] A.U. Raghunathan, V. Gopal, D. Subramanian, L.T. Biegler, and T. Samad. 3D conflict resolution of multiple aircraft via dynamic optimization. *AIAA Guidance, Navigation, and Control Conference and Exhibit*, (AIAA 2003-5675), 2003.

[76] E. Rimon and D. Koditschek. Exact robot navigation using artificial potential functions. *IEEE Transactions on Robotics and Automation*, 8(5):501–508, 1992.

[77] G. P. Roussos, G. Chaloulos, K. J. Kyriakopoulos, and J. Lygeros. Control of multiple non-holonomic vehicles under uncertainty using model predictive control and decentralized navigation functions. 47th *IEEE Conference on Decision and Control*.

[78] RTCA. Minimum aviation system performance standards for the automatic surveillance-broadcast (ads-b), do-242a, 1998.

[79] D. Dimarogonas S. Loizou and K. Kyriakopoulos. Decentralized feedback stabilization of multiple nonholonomic agents. *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 3012– 3017, 2004.

[80] B.G. Sundqvist. Auto-ACAS - robust nuisance-free collision avoidance. *Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference*, pages 3961–3963, 2005.

[81] C. Tomlin, I. Mitchell, and R. Ghosh. Safety verification of conflict resolution maneuvers. *IEEE Transactions on Intelligent Transportation Systems*, 2(2), 2001.

[82] C. J. Tomlin. Hybrid control of air traffic management systems. *Ph.D. dissertation, Departement of Electrical Engineering, University of California, Berkeley*, 1998.

[83] C. J. Tomlin, G. J. Pappas, and S. S. Sastry. Conflict resolution for air traffic management: A study in multiagent hybrid systems. *IEEE Transactions on Automatic Control*, pages 509–521, 1998.

[84] C. J. Tomlin, J. Lygeros, and S. S. Sastry. A game theoretic approach to controller design for hybrid systems. *Proceedings of the IEEE*, pages 949–970, 2000.

[85] P.B.M Vranas, D. Bertsimas, and A.R. Odoni. Dynamic gound-holding policies for a network of airports. *Transportation Science*, 28:275–291, 1994.

[86] P.B.M Vranas, D. Bertsimas, and A.R. Odoni. The multi-airport ground holding problem in ait traffic control. *Operations Research*, 42:249–261, 1994.

[87] C. Wanke and D. Greenbaum. Incremental, probabilistic decision making for en route traffic management. *Air Traffic Control Quarterly*, 15 (4):299–319, 2007.

[88] L.C. Yang and J.K. Kuchar. Prototype Conflict Allerting System for Free Flight. *AIAA Journal of Guidance, Control, and Dynamics*, 20 (4), 1997.

[89] M. Zavlanos. Decentralized motion control of multiple mobile robots, diploma thesis. *Control Systems Lab, Mechanical Engineering Departement, National Technical University of Athens*, 2002.

[90] K. Zeghal. A review of different approaches based on force fields for airborne conflict resolution. *AIAA Guidance, Navigation and Control Conference*, 1998.

[91] K. Zeghal. A comparison of different approaches based on force fields for coordination among multiple mobiles. *Proceedings of the IEEE Conference on Intelligent Robots and Systems*, 1998.